REMARKS/ARGUMENTS

Information Disclosure Statement failure to comply with 37 CFR 1.98(a)(2)

A copy of the publication is attached entitled "Novel Horn Designs for Ultrasonic/Sonic Cleaning Welding, Soldering, Cutting and Drilling" by Sherrit et al. is enclosed.

Drawing objections under 37 CFR 1.83(a)

The reflector in Figures 6 was mistakenly omitted from the original figure and a corrected drawing was made as shown on page 5 of this paper. The reference number 106 has been changed to 102 to be consistent with the text of the description in Figure 7 which is shown on page 6 of this paper.

The following text is required to be added to the end of paragraph [018] of the Detailed Description of the Preferred Embodiment Section-

"A reflector **152** at the base of the fold can be attached to control the phase of the reflected strain wave in the solid body is shown in Figure 6."

Claim Rejection under – 35 USC § 102

The rejection of claim 1 under **35 USC § 102** as anticipated by Nakamura et al. (US Patent 5,896,460) is respectfully traversed. The Nakamura et al. disclosure teaches the use of a apparatus for generating sound from an actuator that comprises a horn (18, 40, 42, 44, 48, 52) as claimed (figures 2-3). Because Nakamura et al. does not teach or suggests the use of a horn to concentrate mechanical vibrations onto a solid or liquid, claims 1-7, are not anticipated.

The rejection of claim 2 and 6 under **35 USC § 102** as anticipated by Nakamura et al. (US Patent 5,896,460) is respectfully traversed. The Nakamura et al. patent concerns a method of coupling vibrations to air to produce a speaker. Nakamura et al. teaches the use of a horn mechanism for radiating sound into air which does not necessitate the focusing of the acoustic energy onto a horn tip. Because Nakamura et al. does not teach or suggest the use of horns with folds that concentrates the mechanical vibrations to a smaller area on the axis of extension, claims 2 and 6, are not anticipated

The rejection of claim 3 and 4 under **35 USC § 102** as anticipated by Nakamura et al. (US Patent 5,896,460) is respectfully traversed. The Nakamura et al. patent teaches the use of a hemispherical shell of piezoelectric material for producing vibrations in air for the purpose of producing a speaker. Because Nakamura et al. does not teach or suggest the use stacked piezoelectric or electrostrictive elements connected concentric and external to the horn and in other embodiments encircled by the horn, claims 3 and 4 are not anticipated.

The rejection of claim 5 under **35 USC § 102** as anticipated by Nakamura et al. (US Patent 5,896,460) is respectfully traversed. The Nakamura et al. patent teaches the use of hollow

core for the purpose of producing a speaker. Because Nakamura et al. does not teach the use of a hollow core that extends through the length of the whole apparatus and does not teach the movement of solid, liquid or gaseous materials from the top of the apparatus through to the bottom of the apparatus , claim 5 is not anticipated.

The rejection of claim 7 under **35 USC § 102** as anticipated by Nakamura et al. (US Patent 5,896,460) is respectfully traversed. The Nakamura et al. patent teaches the use reflectors for the reflection of sound waves in air. Because Nakamura et al. does not teach the use of reflectors for reflecting the acoustic energy in the solid body of the horn, claim 7 is not anticipated.

Novel Horn Designs for Ultrasonic/Sonic Cleaning Welding, Soldering, Cutting and Drilling

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ABSTRACT

A variety of Industrial applications exist where power ultrasonic elements such as the ultrasonic horn are used. These included the Automotive, Instruments, Foods, Medical, Textiles and Material Joining and Fabrication Industries. In many of these devices the ultrasonic horn is the key component. The standard transducer used in these devices consists of three main parts, the backing, the piezoelectric elements and the horn. Standard horn designs have changed very little since their inception. There are four common types of standard horns. They are; constant, linear, exponential and stepped, which refer to the degree to which the area changes from the base to the tip. A magnification in the strain occurs in the horn that in general is a function of the ratio of diameters. In addition the device is generally driven at resonance to further amplify the strain. The resonance amplification is in general determined by the mechanical Q (attenuation) of the horn material and radiation damping. The horn length primarily determines the resonance frequency. For a 22 kHz resonance frequency a stepped horn of titanium has a length of approximately 8 cm. Although these standard horns are found in many current industrial designs they suffer from some key limitations. In many applications it would be useful to reduce the resonance frequency however this would require device lengths of the order of fractions of meters which may be impractical. In addition, manufacturing a horn requires the turning down of the stock material (eg. Titanium) from the larger outer diameter to the horn tip diameter, which is both time consuming and wasteful. In this paper we will present a variety of novel horn designs, which overcome some of the limitations discussed above. One particular design that has been found to overcome these limitations is the folded horn. In this design the horn elements are folded which reduce the overall length of the resonator (physical length) but maintain or increase the acoustic length. In addition initial experiments indicate that the tip displacement can be further adjusted by phasing the bending displacements and the extensional displacements. The experimental results for a variety of these and other novel horn designs will be presented and compared to the results predicted by theory.

Keywords: Piezoelectric devices, Ultrasonic/sonic driller/corer (USDC), inverse horn, folded horn, ultrasonic drilling, planetary exploration, piezoelectric devices, Active Materials.

1. INTRODUCTION

A variety of industrial applications exist where power ultrasonic elements such as the ultrasonic horn are used. These included the Automotive, Instruments, Foods, Medical, Textiles and Material Joining and Fabrication Industries[1,2,3,4]. In many of these devices an ultrasonic horn is the key component of the actuation mechanism. The standard transducer used in these devices consists of three main parts, the backing, the piezoelectric elements and the horn (See Figure 1). A horn is used to amplify the induced strain and it is a solid of length L that is in contact with the piezoelectric material. Horns are generally configured as a tapered solid with a smaller diameter at the tip. The tapering of the area of the horn is used to amplify the limited displacement of the piezoelectric material. Standard horn designs have changed very little since their inception. There are four general designations of standard horns. They are; constant, linear, exponential and stepped, which refer to the degree to which the area changes from the base to the tip. A magnification in the strain occurs in the horn that in general is a function of the ratio of diameters. In addition the device is generally driven at resonance to further amplify the strain. The resonance amplification is determined by the mechanical Q (attenuation) of the horn material and radiation damping while the horn length primarily determines the resonance frequency. For a 22 kHz resonance frequency a stepped horn of titanium has a length of approximately 8 cm. Although these standard horns are found in many current industrial designs they suffer from some key limitations. In many applications it would be useful to reduce the resonance frequency necessitating the use of longer horns. Though the horn can be of the order of fractions of meters long in many applications size is of a premium. In addition, manufacturing a horn such as shown in Figure 1 requires the turning down of the stock

titanium from the larger outer diameter to the horn tip diameter, which is both time consuming and wasteful. In the following paper we present our analysis on a variety of new horn designs and compare the results to initial experimental measurements

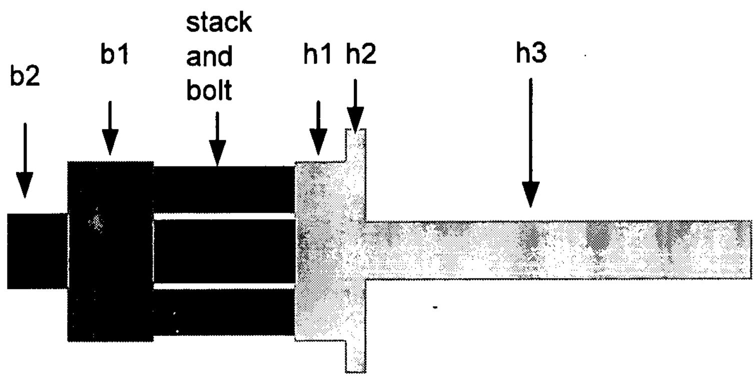


Figure 1. A standard stepped horn (three steps)

2. THEORY

The theory for the standard horn as shown in Figure 1 has been known for over 4 decades[5]. Recently the one-dimensional model was extended to include the piezoelectric stack and the backing[6]. A schematic of the circuit for this model is shown in Figure 2. The parameters of the model shown are calculated using the material constants of the piezoelectric and the elastic properties of the horn and backing material[6]. For the case of an axis-symmetric terminating horn impedance of arbitrary cross section and length L the functional form of the terminating impedance can be calculated using[4]

$$\frac{\partial^2 u}{\partial x^2}+\frac{1}{A(x)}\frac{dA(x)}{dx}\frac{\partial u}{\partial x}=\frac{1}{v^2}\frac{\partial^2 u}{\partial t^2} \tag{1}$$

where A(x) is the functional form of the cross sectional area. dA(x)/dx is the derivative, v is the velocity and the density ρ is assumed to be constant although the equation shown in 1 can be rewritten to accommodate spatial dependencies of the density[7]. An alternate method is to calculate the horn impedance by adding the networks of three acoustic layers and solving for an acoustic short on the horn tip. This solution assumes that the area change between layers is kept small in order to approximate the smooth profile. Additionally, the solution can be solved numerically using Finite Element Packages such as ANSYS[8]. The displacement of the horn tip, resonant frequency and parasitic modes can be determined using a combination of modal and harmonic analysis. A variety of novel horns have been investigated including the inverted shown in Fugure 3, the folded horn shown in Figure 4 and the flipped horn shown in Figure 5. In a folded horn as is shown in Figure 5 the tip displacement can be further adjusted by including bending displacements. By adjusting the fold thickness one can increase or decrease the bending contributions to the tip displacement. This gives the transducer designer another degree of freedom in the horn design. The inverted horn is similar to the standard horn however the horn tip is a ring rather than a solid rod. In the doubly folded horn the horn starts out as an inverted horn with the same area ratio. (cross sectional area of the shell is the same as the cross sectional area of the horn tip of Figure 1.) At approximately 1/3 the length of the standard horn the shell is folded back towards the base and the thickness of this length of shell is adjusted to maintain the same area ratio. Finally as the horn approaches the base it is turned once again to form a solid tip. The flipped horn is similar in shape to the standard horn, however it is driven on what is usually considered the lower face of its larger diameter by a specially designed piezoelectric stack that the horn extends through, thereby minimizing device length without altering horn design.

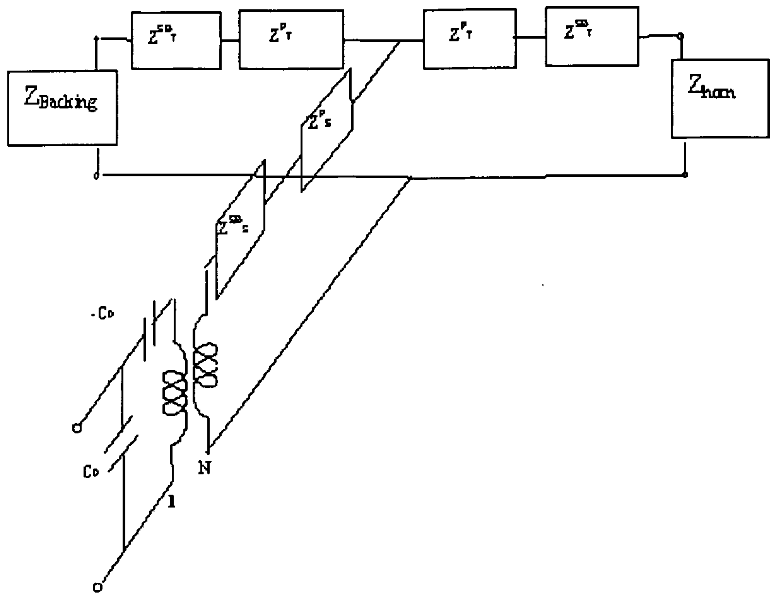


Figure 2. Mason's equivalent circuit for a piezoelectric ring stack with a center stress bolt. Parameters of the model can be found in earlier work[6, 9] Excellent agreement between the full model and experimental results were reported.

A variety of standard horns have been reported previously however for a given ratio of base diameter to tip diameter the stepped horn has the largest strain amplification[5] and can be shown to be proportional to $(D_1 /D_2)^2$ where D_1 is the base diameter and D_2 is the tip diameter. Since the wavelength of the ultrasound is twice as large as the length of the standard horn the extension to the inverted horn is mathematically trivial since the wave does not to first order see any change in the acoustic velocity except for a modest decrease in the longitudinal velocity due to the reduction of clamping. In the folded horn two effects need to be considered. The first is the possibility of bending moments at the turnaround points and the other is the change of direction of the longitudinal strain wave in the mid section of the fold. In pure extension the outer and inner sections of the folded horn extend however the extension in the midsection of the horn can counteract the extension in the other sections. This effect should have little effect on the electrical impedance of the horn even thought it can have a large effect on the velocity output at the horn tip.

3. RESULTS

In order to investigate the one-dimensional model a series of FEM modal and harmonic simulations were performed on inverted, single and double folded horns. An axis-symmetric view of the models is shown in Figure 6. The inverted and folded horns are designed to keep the acoustic length and the cross sectional areas the same as those for the standard horn. The axis of rotation runs vertically on the left side of the devices shown.

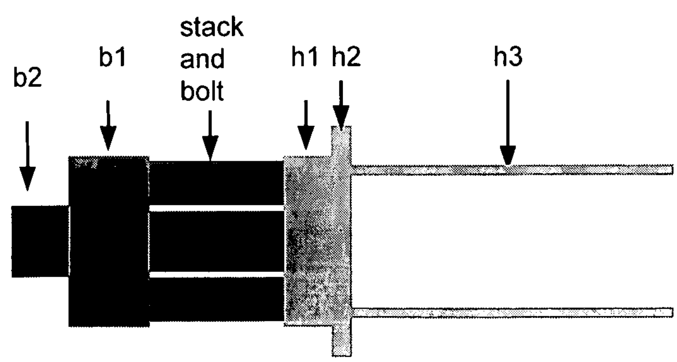


Figure 3. An inverted stepped horn (three steps)

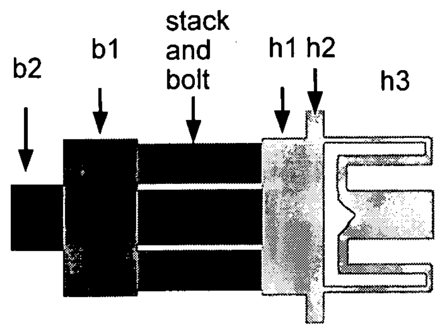


Figure 4. A schematic of a folded horn (2 folds)

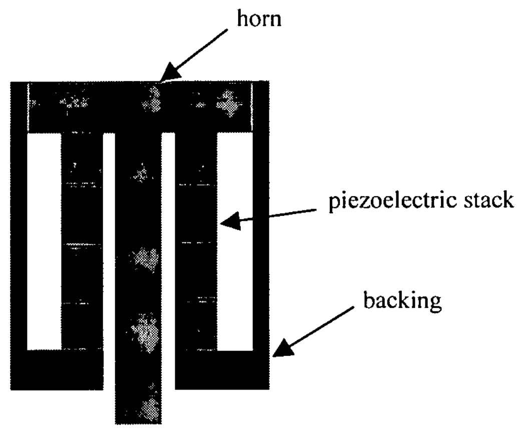


Figure 5. A schematic drawing of a flipped horn. The piezoelectric stack is concentric with the horn tip and generates a stress at the top surface of the horn base. The stress bolt is external and can be configured to modify the resonance frequency.

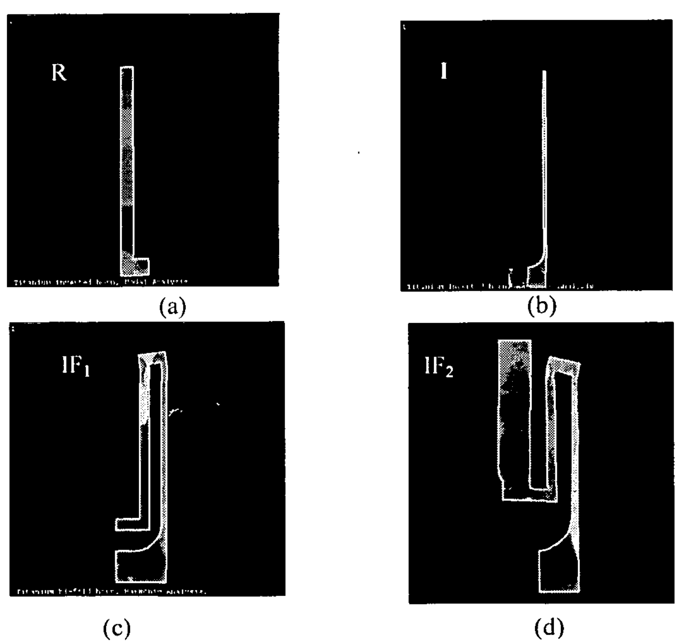


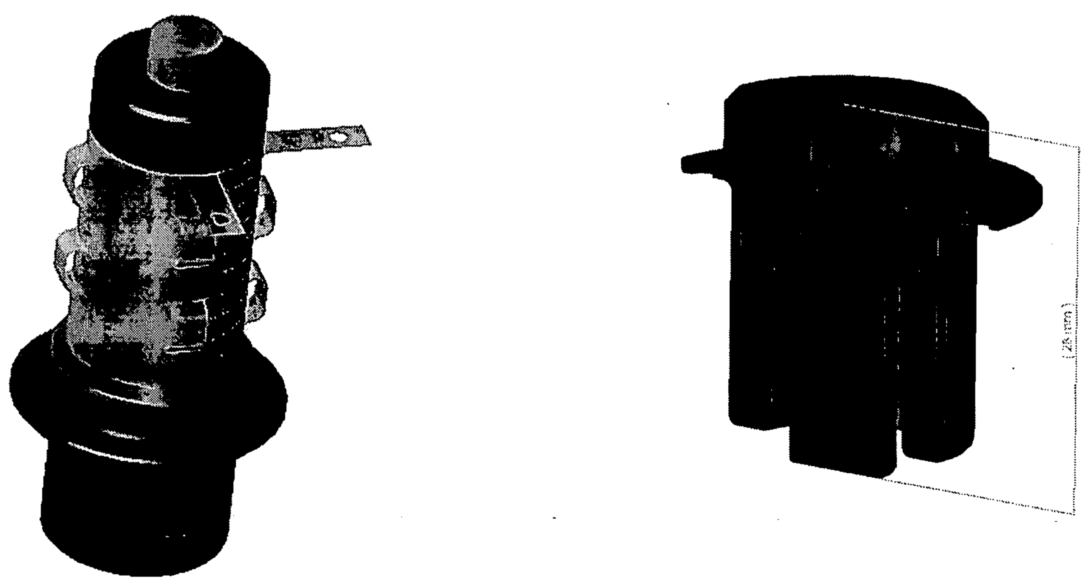
Figure 6. ANSYS axis-symmetric mesh of the a) regular stepped horn R, b) inverted stepped horn IF_0, c) inverted stepped horn with 1 fold IF_1 and d) the inverted stepped horn with 2 folds IF_2.

It should be noted that we have shown only inverted folded horns however one can visualize regular folded horns (RF_0, RF_1, RF_2, etc.) and combinations of the two folded horn types connected mechanically in series. Table 1 lists the horn type and the 1st length extensional resonance frequency determined from the ANSYS modal analysis.

Table 1. List of the resonance frequencies for the various horn types. Acoustic length and cross sectional area is kept constant to first order. The frequency is also shown as a function of the thickness of the fold.

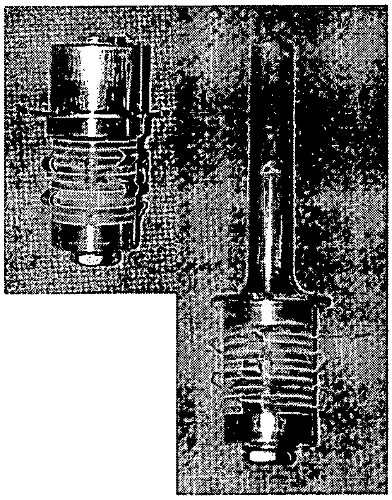
Horn Type	Resonance Frequency (kHz)
Regular R	18.3
Inverted no folds IF_0	18.3
Inverted one folds IF_1 (2 mm thick fold)	14.7
Inverted one folds IF_1 (4 mm thick fold)	16.0
Inverted one folds IF_1 (6 mm thick fold)	16.0
Inverted two folds IF_2(2 mm thick fold)	14.1
Inverted two folds IF_2(4 mm thick fold)	16.2
Inverted two folds IF_2(6mm thick fold)	16.4

The FEM results on the folded horn displayed a variety of behavior including extension in the inner and outer sections as well as the midsection of the horn. The fold width was found to affect the resonance frequency of the device below a few millimeters, which was likely due to bending at the fold. This suggests that the fold thickness can be used to fine-tune the resonance of the device. In order to test the validity of the FEM results a folded horn was fabricated as shown in Figure 7 and 8.



(a) (b)

Figure 7. A Solidworks assembly drawing of the (a)folded horn, piezoelectric stack actuator, and backing. (b) Cross section of the folded horn.



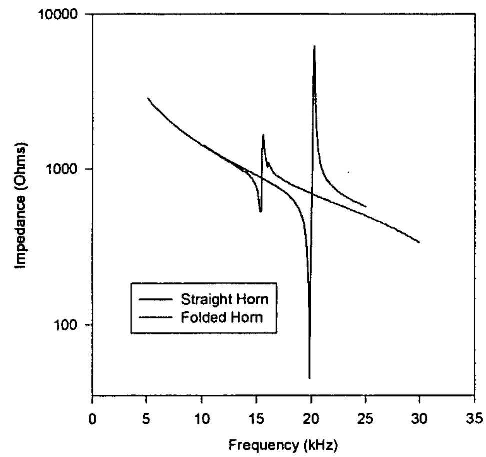


Figure 8. Photograph of the folded horn (16 kHz) and a comparison of a straight horn with approximately the same frequency (20 kHz). A substantial decrease in the resonance is found

The impedance spectra of the folded horn and a standard horn are shown in Figure 8. The standard horn designed for the Ultrasonic Rock Abrasion Tool URAT was determined to have a resonance frequency of approximately 20 kHz while the folded horn was found to resonate at approximately 16 kHz. Another noticeable difference was in the size of the resonance. The mechanical Q of the folded horn was a factor of ten below the standard straight horn. This had a detrimental effect on the displacement measured on the tip of the folded horn. It was also a factor of 10 roughly smaller (10 microns as compared to > 100) than the straight horn. Upon closer inspection of this folded horn design it was determined that the screw threads connecting the base plate of the horn to the outer walls of the horn were the likely source of the increased dissipation of energy and reduction of resonance. Another design without screw threads that can be manufactured quite easily, which we are currently investigating, is shown in Figure 10.

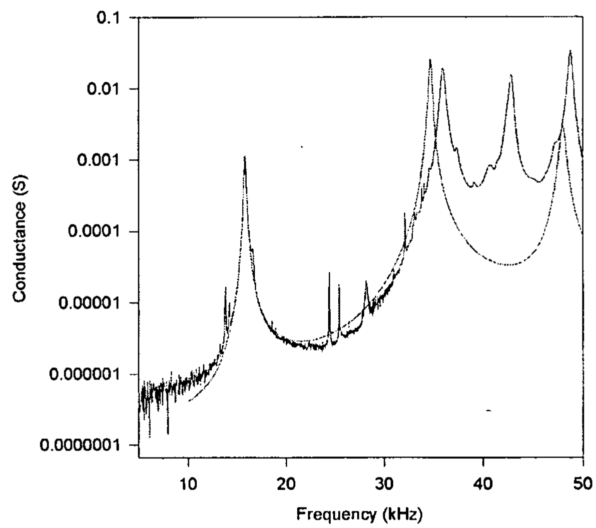


Figure 9. The impedance spectra of the folded horn compared to the standard model. In order to match the amplitude of the fundamental peak the quality of the horn material had to be reduced by a factor of 10. The reduced resonance amplitude in the impedance values for the folded horn is the result of the lower Q of the device, which is likely caused by poor energy transfer across the screw threads in the base.

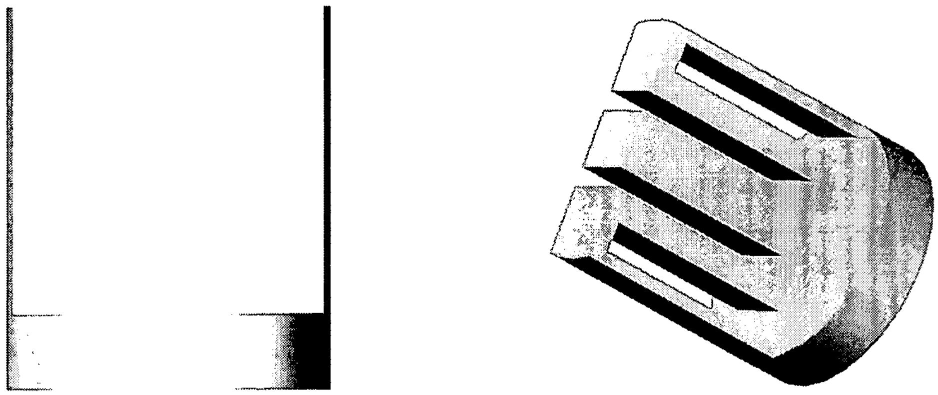


Figure 10. Solidworks model of a folded horn that does not require a threaded base.

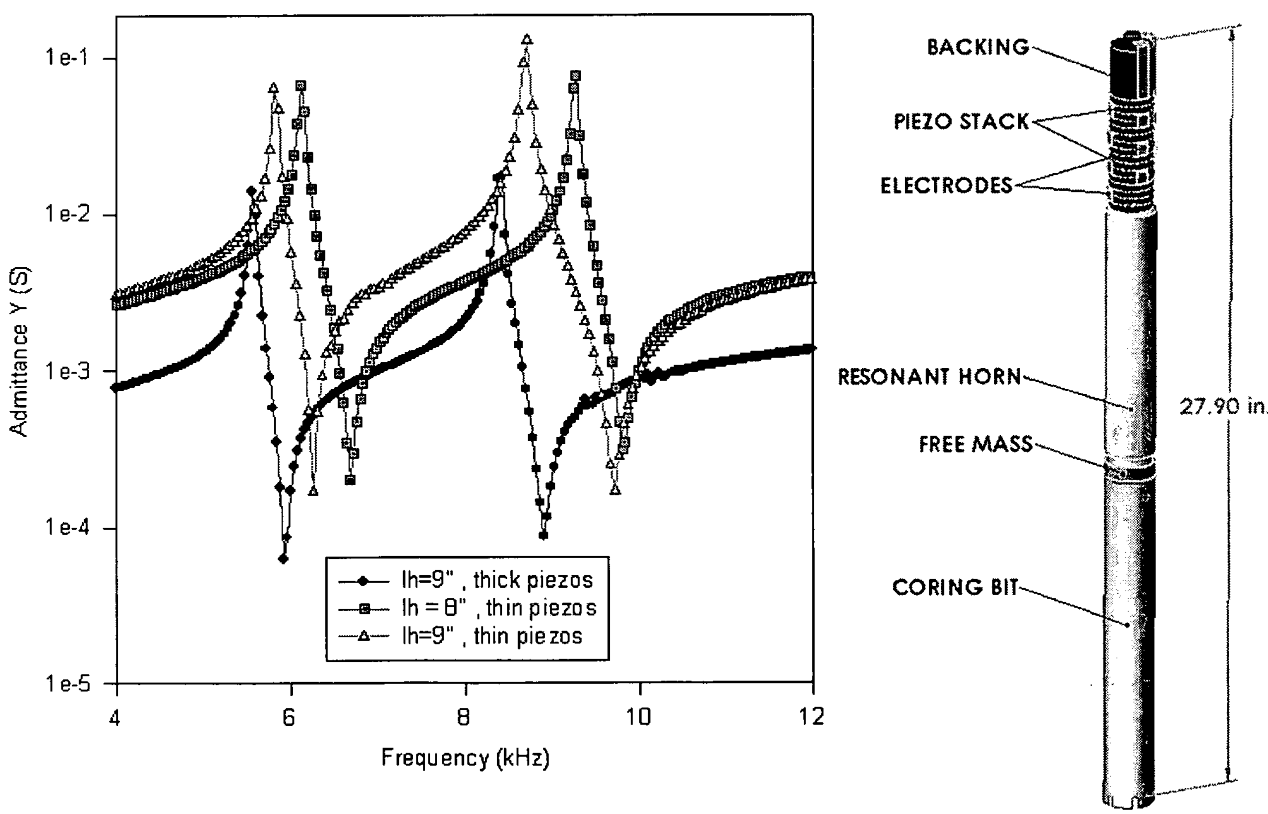


Figure 11. The impedance spectra of the large inverted horns designed for the ultrasonic gopher shown to the right. By adjusting the piezoelectric thickness and reducing the horn length we were able to adjust the baseline impedance, the resonance frequency and the impedance at resonance. The latter is useful with regards to impedance matching of the driver and the device.

Another horn type that we investigated is the inverted horn which is a tube structure connected to a solid base which is excited using a stack of piezoelectric elements. This horn type was chosen for the ultrasonic Gopher shown to the right in Figure 11. The ultrasonic Gopher is a deep drilling device that has recently been designed and tested at JPL. The device is designed to be driven at high power levels (> 200 Watts). In order to drive the device with an amplifier with 25-50 Ohm output the impedance spectra were measured for different configurations of horn length and piezoelectric element thickness (and number). The results are shown in Figure 11. The fundamental resonance frequencies of these devices were measured to be between 5.5 and 7 kHz. The gopher demonstrated drilling a 10 cm long, 4.0 cm diameter hole in limestone using a 200W power supply. Efforts are currently underway to increase the efficiency of this low frequency device.

4. CONCLUSIONS

A variety of horn designs were presented including the inverted, folded and flipped. The inverted horn was found to behave acoustically in a similar manner to the standard stepped horn with a slight reduction in the acoustic velocity in the horn material due to reduced clamping in the tube. The folded horn was investigated and found to produce resonances in the frequency range of the standard horn even though the device was approximately half the size. Finite element analysis of the folded horn suggests that bending modes at the turnaround points can be used to accentuate the extension of the horn tip. Tests on the prototype folded horn were found to match data generated using the material constants however the quality of the resonance was reduced by a factor of 10 from the Q of the standard horn. This reduction was believed to be due to the threads in the base of the horn and a new design without threads in the acoustic path was suggested. A flipped horn was conceived in which the stack was concentric with the horn tip allowing for a reduction in the length of the overall actuator. Studies are currently underway to determine the feasibility of this approach.

ACKNOWLEDGEMENTS

The Mars Exploration Technologies under a contract with the National Aeronautics Space Agency (NASA) funded the research at the Jet Propulsion Laboratory (JPL), a division of the California Institute of Technology.

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